Continued Investigation of the Acoustics of Marine Sediments Using Impedance Tube and Acoustic Resonator Techniques

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LONG-TERM GOALS

The main goal of this project is to increase our understanding of sound propagation in ocean bottom sediments, including ocean bottom multiphase material such as gas-bearing sediments and seagrass, which in turn benefits buried object detection, sonar operation and acoustic communications in shallow water. Another goal for the out years is to develop the proposed research apparatus into an operational system for *in situ* classification of ocean bottoms for Naval fleet operations.

OBJECTIVES

The primary objective is to obtain experimental measurements of sound speed and attenuation in a variety of natural and artificial ocean bottom sediments, including multiphase materials such as gas-bearing sediments and seagrass. These measurements are conducted using an acoustic resonator tube [1, 2] method, in the frequency range of approximately 300 Hz to tens of kHz, and using a traditional time-of-flight approach at frequencies from a few hundred kHz up to a few MHz. These measurements will span a frequency range in which there is little experimental data obtained with a single sediment parcel, and thereby help to verify existing [3-10] and developing [11-13] theoretical models for sound propagation in these materials. An overview of the state-of-the-art in both direct experimental measurement and modeling for water-saturated sand from a single location is shown in Fig. 1. Note the lack of data below a few kHz and the inability of a single model to correctly describe both the sound speed and the attenuation, although new models [11-13] yet to be fully unified and applied to this data may show better agreement at high and low frequencies. New collections of sound speed and attenuation data inferred from shallow water propagation measurements have also recently been analyzed and published [14] which show good agreement between the average, global behavior of granular marine sediment and the Biot-based model, at least in that the model can bound the data within a reasonable range of input parameters. Despite these recent advances, measurement still lags behind modeling for all the ocean bottom materials discussed thus far. Our goal is to provide measurements on single parcels of sediment with sufficient accuracy, precision and understanding of measurement uncertainty to validate the modeling efforts. We also seek to observe the effect of varying grain size, distributions of grain size, and particle shape, the latter to investigate grain contact

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14. ABSTRACT
The main goal of this project is to increase our understanding of sound propagation in ocean bottom sediments, including ocean bottom multiphase material such as gas-bearing sediments and seagrass, which in turn benefits buried object detection, sonar operation and acoustic communications in shallow water. Another goal for the out years is to develop the proposed research apparatus into an operational system for in situ classification of ocean bottoms for Naval fleet operations.

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physics. Gas bearing sediments are present in many parts of the world, and there has been even less experimental verification of the acoustic behavior of these sediments. We seek to apply our measurement/modeling comparison approach to gas bearing sediments, too. Finally, seagrass can partially or fully obscure mines, and we are also interested in understanding the acoustic behavior of this material, with the aim to eventually exploit phenomena associated with the seagrass tissue gas content, or the free gas that is resirated by seagrass during photosynthesis. A secondary objective has been to continue to analyze data collected during the ONR sea test Shallow Water 06 (SW06) and to develop new measurement instrumentation for future ONR basic ocean acoustics sea tests.

APPROACH

In this fiscal year, for our primary research objective, we have focused on the resonator method [1, 2] of measuring acoustic properties and have constructed a new apparatus for high frequency measurements. For the former, we have added the capability to control the hydrostatic pressure of the sediment samples, so that measurements can be done at simulated ocean depths, which is important for gas-bearing sediments. The resonator apparatus and pressure vessel are shown in Fig. 2. For the latter, we have adopted a technique that allows for the control of porosity, [15] and has been applied to new high frequency (above 50 kHz) measurements, presented below. We also incorporated a normal incidence reflection measurement capability into this system. This new system allows for the simultaneous measurement of sound speed, attenuation, and normal incidence reflection in water-saturated granular materials as a function of frequency and porosity. Reflection measurements on glass bead sediments have recently been conducted, but the analysis of this data is not complete. For the secondary objective, shallow water acoustic propagation data from the recent SW06 experiment has been analyzed and compared to model predictions. Finally, the combustive sound source (CSS) is being developed for use in future ONR-sponsored ocean acoustics experiments. The CSS will serve as a replacement for explosive charges and air guns in future basic research sea tests.

The personnel for this project are: Preston S. Wilson serves as PI and is an Associate Professor in the Mechanical Engineering Department at the University of Texas at Austin (UTME), and is also an Associate Research Professor at the University's Applied Research Laboratories (ARL:UT). In addition to oversight, Wilson contributes significantly to many tasks, including modeling, instrument and experiment design, construction and operation. Kevin T. Hinojosa, a UT Aerospace Engineering junior and an Undergraduate Research Assistant on the project, serves as an electromechanical technician and provides machine shop, procurement and software support. Theodore F. Argo IV is a UTME Ph.D. student who contributes to all aspects of the project. Another UT MS student, Christopher J. Wilson is also working on the seagrass acoustics portion of this project. Chris is primarily funded by a fellowship he holds, but he contributes to this effort.

WORK COMPLETED

Primary Objectives—Laboratory Sediment Investigation: We began a collaboration with a research group in the University of Texas at Austin's physics department that studies the dynamics of granular material and also with a group at The Max Plank Institute for Dynamics and Self-Organization (Göttingen, Germany). We adapted a technique they jointly developed [15] to create samples of water-saturated granular materials with variable porosity using a fluidization technique. We have conducted a series of sound speed and attenuation measurements [16] at high frequencies (300–800 kHz) in glass-bead sediments with a porosity range from 0.38 to 0.44 and compared them to the predictions of the Biot-Stoll model. [9] The apparatus and results are shown in Fig. 3.

Leveraging funding from another project, the PI participated in the arctic research cruise Methane in the Arctic Shelf (MITAS) aboard the USCGC Polar Sea in the Beaufort Sea, on the continental shelf off the North Slope of Alaska in September 2009. The goal of this cruise was to study methane transport from sediments containing methane hydrate, up through the sediment, into the water column, and ultimately the atmosphere. Our part was to measure the acoustic properties of gas-bearing sediments, but we also had the opportunity to measure the sound speeds in a number of silt, mud and clay sediments. Data analysis is currently underway. Some images of the cruise are shown in Fig. 4.

Primary Objectives —Gas-bearing Sediments: We continued our collaboration with the Seafloor Sciences Group at NRL-SSC on the acoustics of gas-bearing sediments. Gas bearing sediments were found during MITAS as mentioned above. Our 1-D acoustic resonator technique [1] was used to measure the sound speed inside the sediment samples. A high frequency (400 kHz) time-of-flight technique using an NRL core logger was also used to measure the high frequency sound speed.

Primary Objectives—Seagrass Acoustics: Our previous collaboration with the seagrass biologist, Dr. Kenneth Dunton, of the University of Texas Marine Science Institute on the acoustics of sediments containing seagrasses has continued. Our acoustic resonator technique was used to make additional measurements of the effective low frequency acoustic properties of three gulf-coast species, *Thalassia testudinum* (turtle grass), *Syringodium filiforme* (manatee grass), and *Halodule wrightii* (shoal grass). These measurements are similar to those previously discussed [17] but have now been accompanied by micro x-ray computed tomography imagery of the leaf and rhizome tissue. Analysis of this data will allow us to determine the volume of gas and the volume of tissue, which in turn will allow us to determine the acoustic properties of the tissue itself. This work is currently underway.

A seagrass acoustics tank facility was constructed this FY using leveraged funds from another internal UT source. This tank will be used to conduct controlled experiments on photosynthetic bubble production and its effect on the acoustics of seagrass beds. Construction of the apparatus was begun this summer and is currently ongoing.

Secondary Objective—SW06 Data Analysis: The combustive sound source (CSS) was deployed by this author and ARL:UT colleagues in SW06. Subsequent data analysis this year built upon last year's analysis [18, 19] and has further shown that CSS is a viable alternative to small explosive charges and better than light bulb implosions.

Further development of the CSS for NAVO ocean surveys was conducted, which impacts ONR code 32 interest in the CSS for future use in basic ocean acoustics sea tests. A larger version of the SW06 CSS was constructed and free-field testing was conducted using funds provided by NAVO. An increased source level, was achieved over the SW06 version of CSS.

RESULTS

Primary Objectives— Laboratory Sediment Investigation: The porosity control apparatus that was designed and constructed to measure the sound speed and attenuation in water-saturated sediments as a function of frequency and porosity is shown in Fig. 3. Water is pumped up through the bead sample, which fluidizes the sediment. The height of the sediment column increases in proportion to the flow rate. When the flow is terminated, the sample settles back to an equilibrium porosity that is higher than the original randomly packed porosity. The resulting equilibrium porosity is a function of the flow rate and flow rate history in a known way, hence one can prepare sediment of a particular porosity. This work is the first that we know of to systematically investigate both frequency and porosity in a single sediment sample. As shown in Fig. 3(a)–(d), we found that the Biot model does a good job of describing the porosity-dependency of granular sediment (spherical glass beads, radius = 250 µm) sound speed at high frequencies. The Biot model underpredicts attenuation at these frequencies, a result others have also observed. [13, 20, 21] We also observed for the first time (to our knowledge) in a single sediment sample, a transition in the frequency dependency of attenuation from the Biot $f^{1/2}$ regime to the f^4 multiple scattering regime. The latter has been observed before, [22] but a transition from one regime to the other so rapidly does appear to have been observed previously. This work is currently under revision and will soon yield a new publication. [16]

Regarding our work on the Polar Sea in the arctic ocean research cruise MITAS: In years past, the shelf area off the Alaskan North Slope (the location of the US's strategic petroleum reserve and the Alaskan pipeline) has been iced over for much of the year, but now, due to climate change, there is open water for a significant part of the year. Standard surface ships can now operate in this region, hence the acoustic properties of this shelf area are of interest. We found primarily silt, mud and clay sediments with perhaps one in ten coring locations showing gravel, and almost no sand. Some of the cores had significant free gas content. Horizontal variation across these sediment types was observed, but there was very little vertical variation in the cores. A typical sound speed profile with a strong surface layer both on the slope and on the shelf is shown in Fig. 4.

Primary Objectives—Gas-bearing Sediments: The collaborative work with NRL-SSC on the Polar Sea during MITAS resulted in the measurement of sound speed in naturally occurring methane gas-bearing sediments. A preliminary low frequency sound speed result is shown in Fig. 5, for a mud sediment sample that contained a homogeneous distribution of methane bubbles. The sound speed was found to be about 200 m/s below 2 kHz and it rose to 1200 m/s at the highest frequency that was used in the measurement. This sound speed dispersion is qualitatively similar to that predicted by Anderson and Hampton [23] and also shown in Fig. 5. Our standard correction for the elastic waveguide effect [2] has yet to be incorporated as this data was just collected the week prior to this report. Contemporaneous core logging measurements, including high frequency sound speed and attenuation, denisty, and magnetic susceptibility were obtained by NRL, and lithostratigraphy and geo/bio chemistry analyses were conducted by other MITAS researchers. This collection of data will ultimately be used to fully characterize the sediment material.

Secondary Objective—SW06 Data Analysis: The combustive sound source (CSS) was deployed by the PI and ARL:UT colleagues in SW06. Subsequent data analysis this year built upon last year's analysis [18, 19] and has further shown that CSS is a viable alternative to small explosive charges and better than light bulb implosions. Both short- and long-range broadband propagation in SW06 has been modeled in an uncertain inhomogeneous waveguide. A typical result is shown in Fig. 6. These and additional results are presented in a new paper, currently in revision. [24] The results of the study suggest that the coherent structure of low frequency long-range propagation in an area of the New Jersey continental shelf known for its environmental complexity can be successfully simulated with a coarse sampling of environmental parameters such as the sound speed profile, the bathymetry, and the geoacoustic profile.

A larger version of the SW06 CSS was constructed and free-field testing was conducted using funds provided by NAVO. An increased source level, was achieved over the SW06 version of CSS, as shown in Fig. 7. The new CSS provides a peak acoustic pressure of 246 dB re 1 µPa @ 1 m, and a peak energy spectral density of 190 dB re 1 μPa^2·s/Hz, with significant energy from below 10 Hz to above 1000 Hz. The utilization of air, as opposed to oxygen was also tested. The resulting signal, also shown in Fig. 7, is less broadband than the hydrogen/oxygen signal, but contains more low frequency energy.

Secondary Objective—Acoustics of Bubbly Liquid: Work completed in a previous years, that was partially supported by this grant was published or presented this year. We studied bubble growth due to rectified diffusion with the goal of helping to assess the effect of sonar on marine mammals. We found that acoustic excitation at realistic levels due to sonar transmissions, would not greatly increase the rate of bubble growth in supersaturated marine mammal tissue, over that of static diffusion alone. [25] This is in part because the actual acoustic pressure level in front of a sonar transducer in never as high as the source level value. The source level is a level that is measured in the far field and scaled back to a range of 1 m, but because of near field diffraction effects, the maximum pressure in front of a radiator is much lower, say about 215 dB re 1 μPa for a source level of 235 dB. We also investigated the use of a laser doppler velocimeter to measure bubble dynamics. [26, 27]

Educational Activities: Our work with bubbles and acoustic resonators previously described lent itself perfectly to two publications [28, 29]{Greene, 2009 #5; Wilson, 2008, wilson:2008} and two presentations [30, 31] geared toward education in underwater acoustics.

IMPACT/APPLICATIONS

The Biot-based description of sound propagation within sandy marine sediments is gaining support in the ocean acoustics and related research communities, but we are also coming to the conclusion that it not fully adequate. The new laboratory results reported here indicate that the Biot-Stoll model [9] correctly predicts the porosity dependency of high frequency sound speed in water saturated sand. Low frequency (53–2000 Hz) attenuation data [19] from SW06 are also well described by Biot-Stoll and clearly follow the low frequency limiting slope of frequency squared. We are continuing our efforts to get ever-more-broadband and more accurate laboratory measurements with an increased understanding of the measurement uncertainties.

Gas-bearing mud sediments were shown to have significant dispersion, with very low sound speeds below about 1 kHz, and an increasing sound speed as frequency increases, as qualitatively predicted by Anderson and Hampton. [23] During the MITAS cruise, the continental shelf above the North Slope of Alaska was found to have slit, mud and clay sediments, and the water column was found to have a prominent sound channel between the surface and 400 m depth. With arctic ice retreating ever further north each year, the coastal regions north of Alaska will likely become area of operation for the Navy. The acoustical environment in this area in absence of the ice pack at the surface is largely unexplored. This area should be considered as a site for future ONR shallow water acoustic experiments.

As our understanding of sound propagation in the ocean bottom increases, one application will be to update the models used in operational sonar systems and environmental surveys. A better description of bottom interaction will increase our ability to detected, localize and classify targets in littoral environments. The same can be said for buried objects. Finally, the CSS continues to provide useful data from SW06 and will be a useful tool for ocean acoustics experiments.

TRANSITIONS

This PI receive $120k in the current fiscal from the Naval Oceanographic Office for further development of the combustive sound source (CSS) as a replacement for explosives in ocean surveys.

This PI received $249k from the ONR Code 332 to perform laboratory measurements of the sound speed in methane hydrates, using the resonator method developed with the present grant, covering FY08, 09 and 10.

This PI started a project in 2009, funded by Shell Oil, to use bubbles to reduce the radiated noise from offshore drilling operations. Much of this PI's experience with bubbles was due to a project previously funded by ONR and also due to the current grant.

RELATED PROJECTS

SAX99: Sediment Acoustics Experiment 1999

From the project web page: SAX99 addresses high-frequency sound penetration into, propagation within, and scattering from the shallow-water seafloor at a basic research (6.1) level.
http://www.apl.washington.edu/programs/SAX99/Program/prog.html

SAX04: Sediment Acoustics Experiment 2004

From the project web page: The overall objective of SAX04 is to better understand the acoustic detection at low grazing angles of objects, such as mines, buried in sandy marine sediments. One component of the SAX04 work is designed to collect data and gain a greater understanding of high-frequency sound penetration into, propagation within, and scattering from the shallow water seafloor at a basic research level. A second component is designed to provide data directly on acoustic detections of buried mine-like objects at low grazing angles.

http://www.apl.washington.edu/projects/SAX04/summary.html

Other ARL: UT sediment researchers: Marcia Isakson and Nicholas Chotiros both conduct research on sound propagation in marine sediments. Many ONR PIs conduct research on modeling of sound propagation in shallow water waveguides.

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HONORS/AWARDS/PRIZES

On December 15, 2009, this grant's PI, Preston S. Wilson was awarded tenure and promoted to Associate Professor in the Mechanical Engineering Department at the University of Texas at Austin, effective September, 1 2009.

Theodore F. Argo IV, a Ph.D. student supported by this grant, won third prize in the Best Student Paper Award of the Acoustical Oceanography Technical Committee of the Acoustical Society of America, for his paper entitled "Laboratory measurements of sound speed and attenuation in water-saturated artificial sediments as a function of porosity," which was given at the Fall 2008 Meeting of the ASA in Miami.

FIGURES

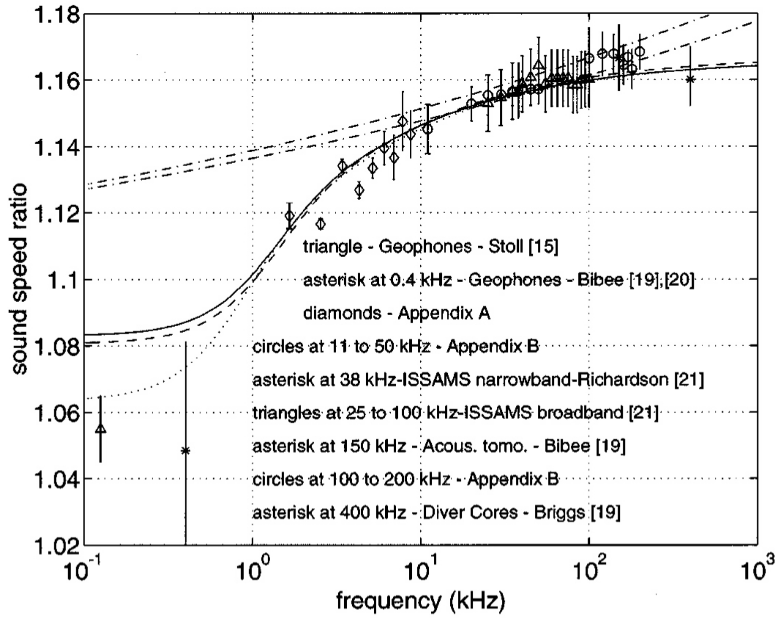

Fig. 1-a. State-of-the-art model/data comparison for the sound speed in a sandy water-saturated sediment. The citations in the legend refer to those in Ref. [32]. The theoretical curves are: solid line=Biot/Stoll [9]; dashed line=Williams [10], dash-dot lines=Buckingham's model for two values of fluid viscosity [8]; dotted line=best fit Biot/Stoll model for input parameters outside of measured values. Note the scarcity of data from the low-kHz and below. Also note that the Biot and Williams models do a better job of predicting the data than the Buckingham model does. (Figure adapted from [32].)

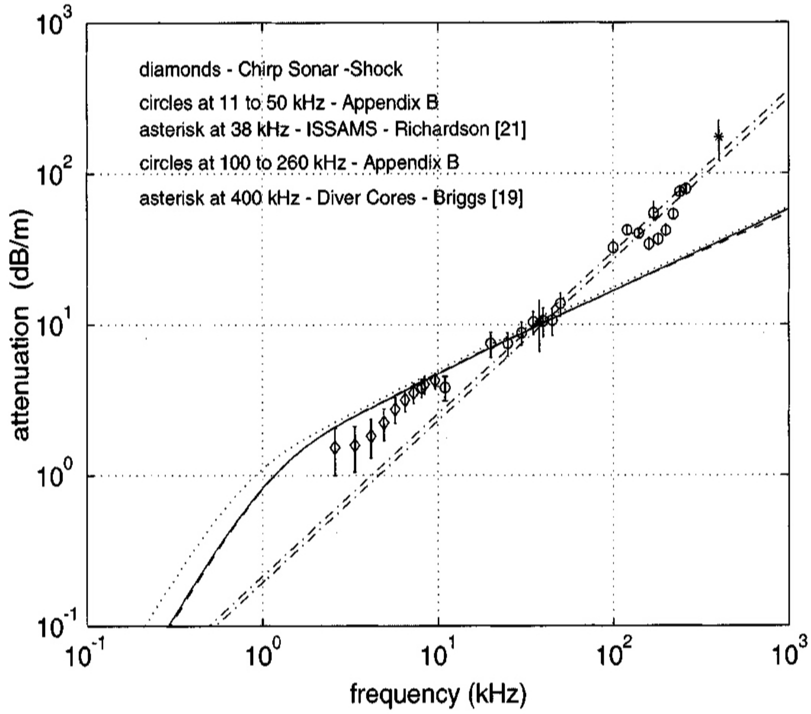

Fig. 1-b. Same as Fig. 1-a, except for attenuation. Note that here, the Buckingham model does a better job of predicting the data than the Biot and Williams models do. (Figure adapted from [32].) Also note that there is no attenuation data below about 3 kHz.

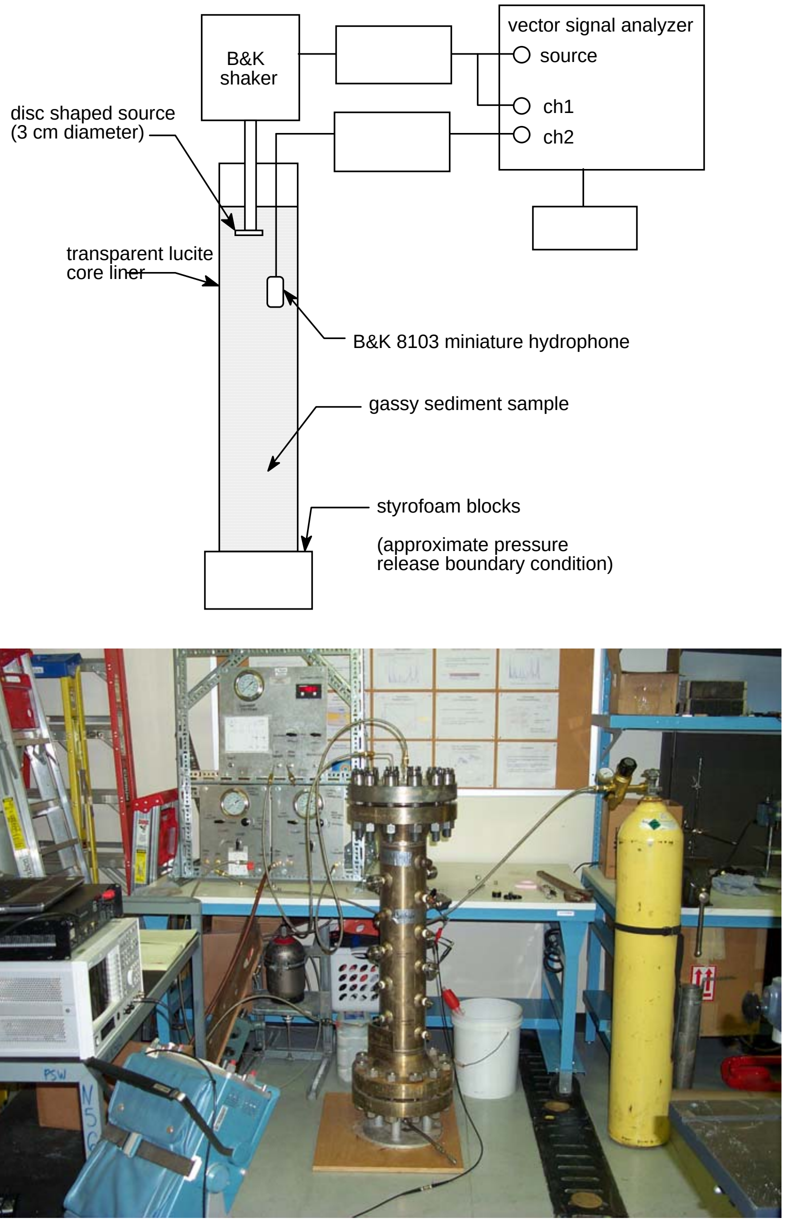

Fig. 2. The upper panel, a schematic of the resonator method is shown. In the lower panel, a photograph of the pressure vessel is shown. The resonator apparatus can be operated inside the pressure vessel to make measurements of sediment sound speed at simulate ocean depths up to 1000 m.

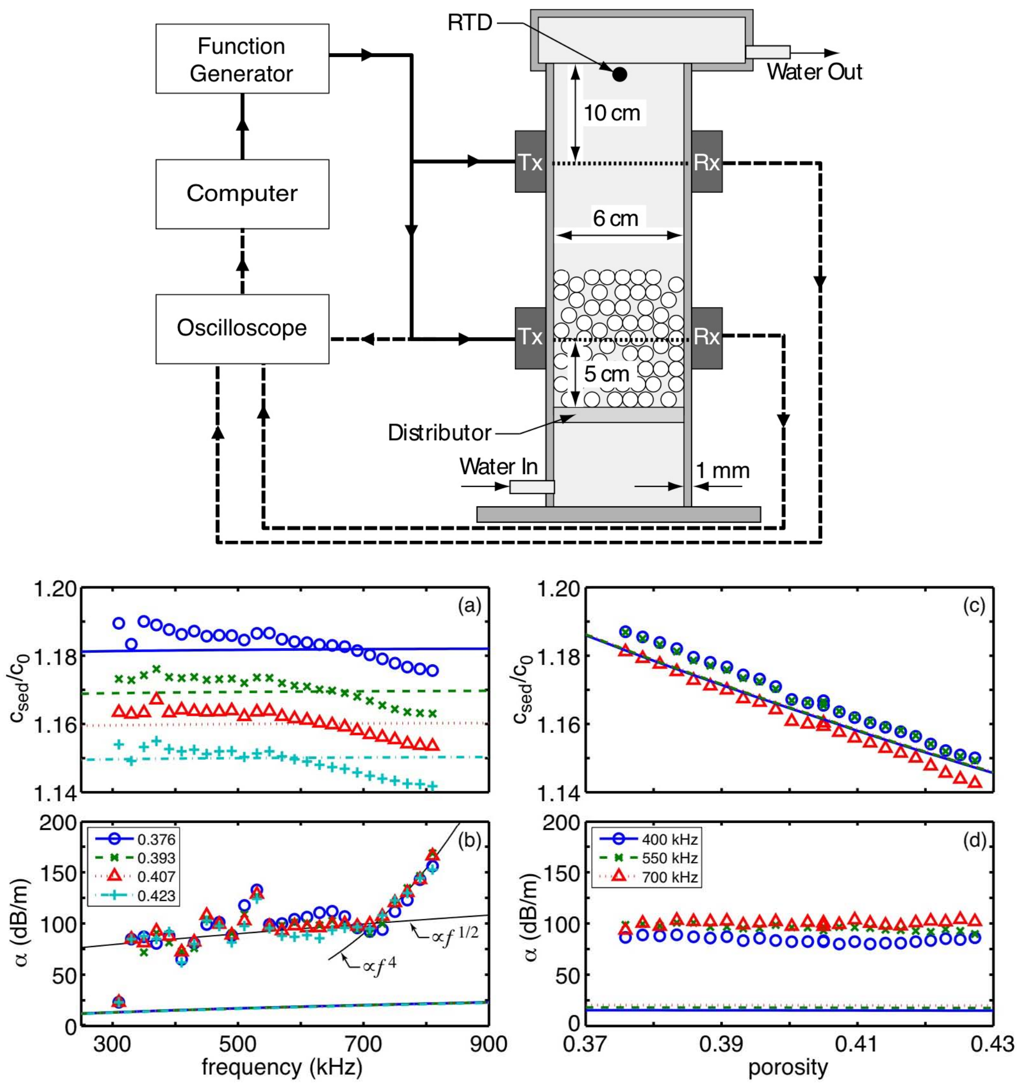

Fig. 3. Upper panel: The high frequency time-of-flight measurement and porosity control apparatus is shown in schematic. Lower panel: Sound speed (a) and attenuation (b) measurements are shown as a function of frequency for four porosities. Predictions of the Williams' effective density fluid model (EDFM) are shown with colored solid and dashed lines. Frequency-dependency trend lines are shown with thin, solid black lines. Notice the shift from $f^{1/2}$ to f^{4} behavior near 700 kHz. Sound speed (c) and attenuation (d) are shown as a function of porosity for three frequencies. Colored solid and dashed lines are EDFM predictions.

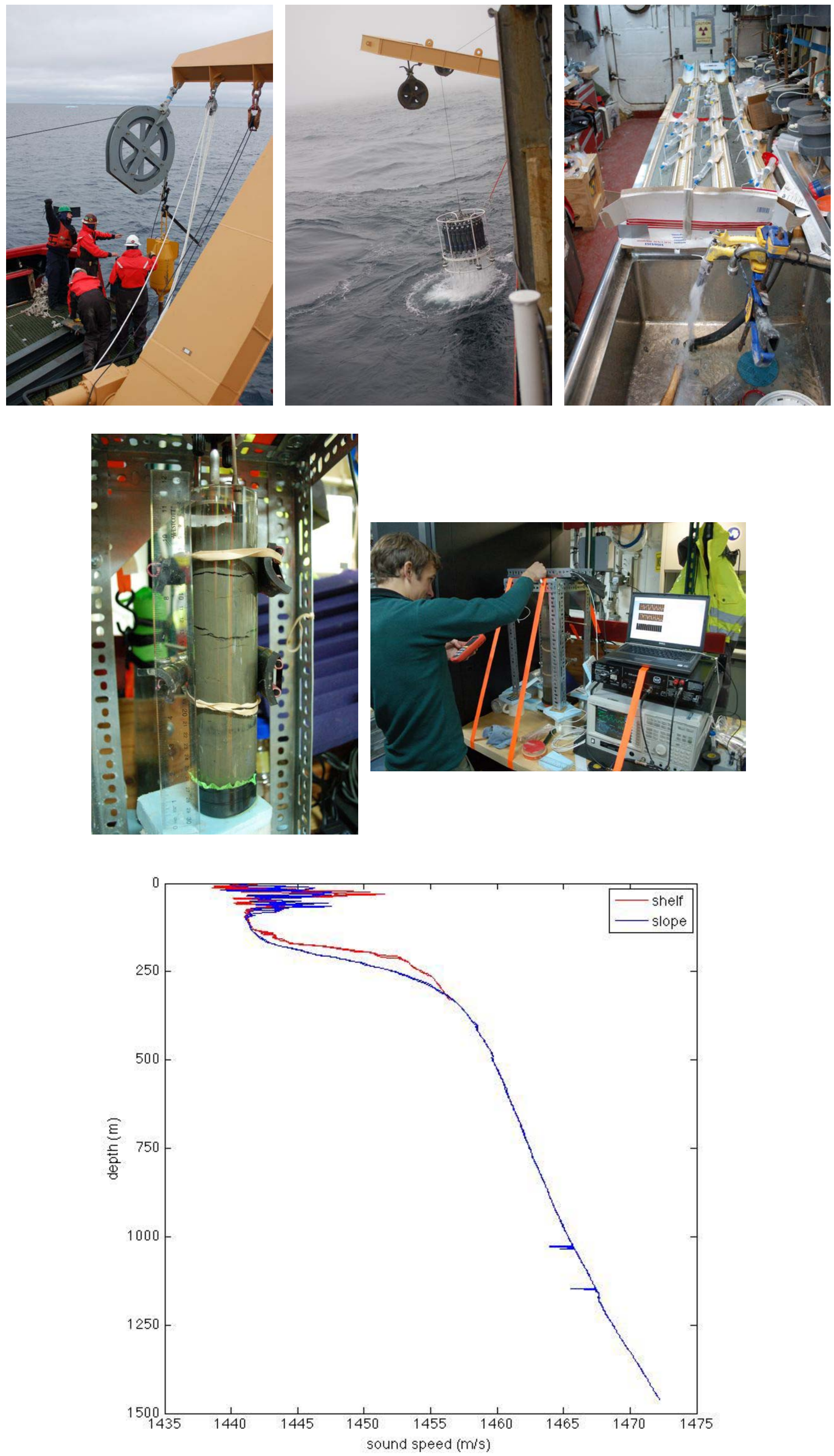

Fig. 4. Images from arctic research cruise MITAS aboard the USCGC Polar Sea in the Beaufort Sea. Top Row L to R: Sediment coring operations , CTD casting, sediment pore water sampling. Middle Row L to R: gas-bearing mud sediment core, acoustic resonator measurements onboard Polar Sea. Bottom Row: Strong sound channel revealed in sound speed profile for both on shelf (red) and in deeper water (blue).

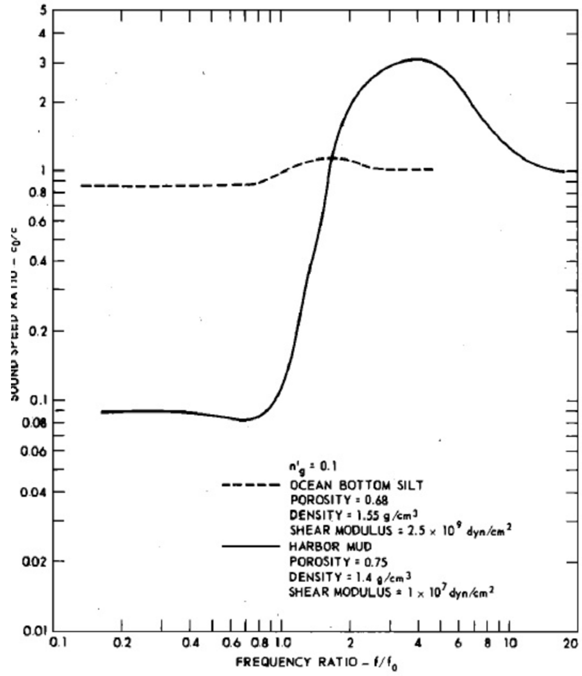

FIG. 15. Gassy sediment sound speed ratio versus frequency ratio.

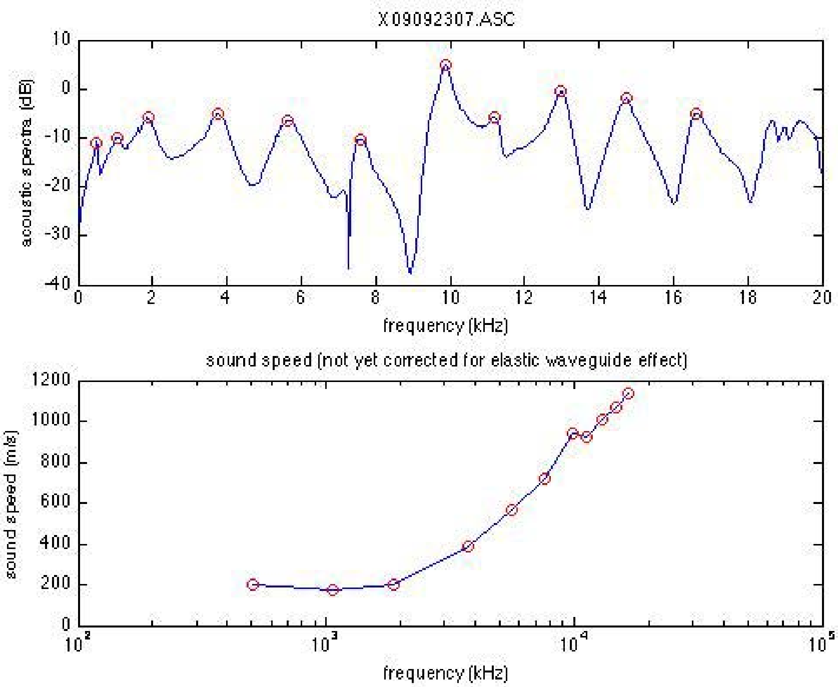

Fig. 5. Top left: A gas-bearing mud sediment from the Alaskan shelf under the Beaufort Sea. Top Right: Predicted sound speed in a gas-bearing sediment from Anderson and Hampton. [23] Bottom: Qualitatively similar sound speed measurements obtained from our 1-D resonator system.

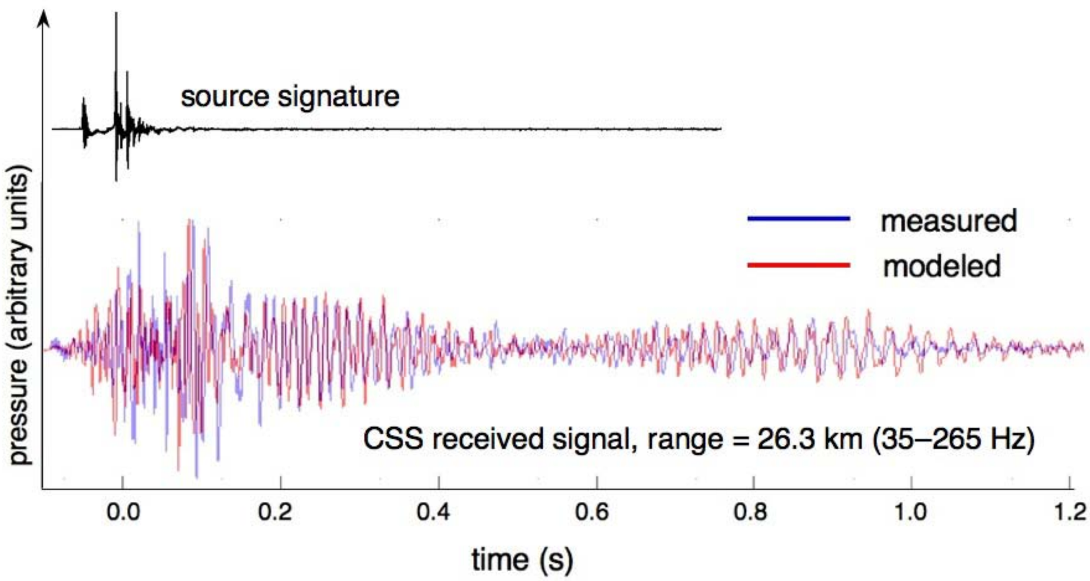

Fig. 6. Broadband propagation modeling from SW06. The upper curve is the CSS Event 26 source signature, deployed at 26 m depth. The lower curves are measured and modeled propagation 26 km downrange from the source.

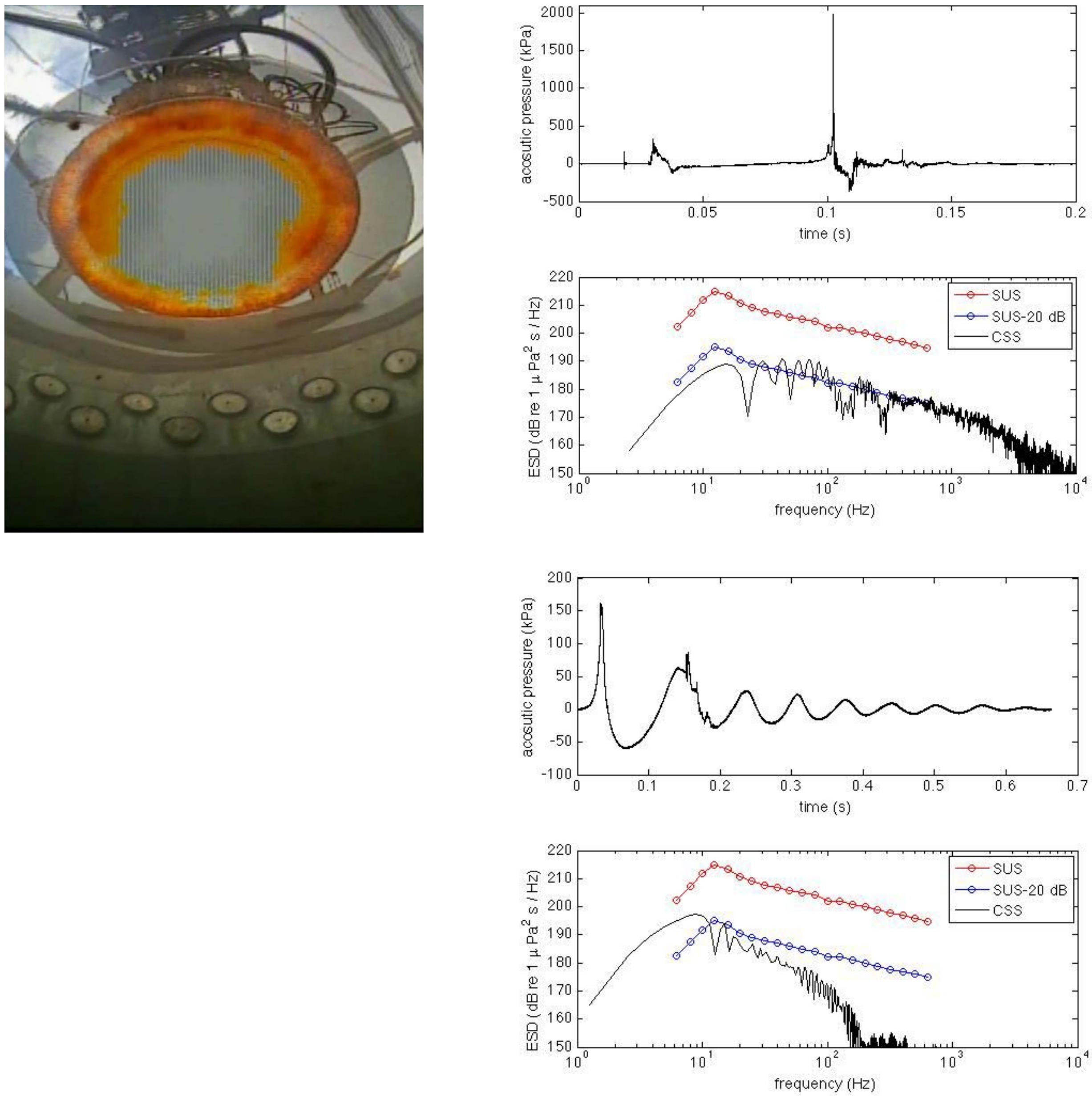

Fig. 7. Upper Left Photo: Combustion and bubble activity produced by the CSS is shown. Upper Right: The radiated acoustic pressure of an increased-output CSS burning hydrogen and oxygen is shown in the upper frame. The corresponding energy spectral density is shown in the lower frame for CSS, for a SUS charge and for a SUS-charge less 20 dB. Lower Right: Same as upper right, except that air was used as the oxidizer instead of oxygen.